

PROJECT COMPLETION REPORT

1. Title of the Project	Development and evaluation of automated sensors for a highly-efficient nutrition management system in Indoor Vertical farming - SensVert
2. Name & Address of the Partner/PI	Hochschule Weihenstephan Triesdorf (HSWT), Am Hofgarten 4, 85354 Freising Prof. Dr. Heike Mempel
3. Name & Address of other Partners	
German Research Partner	M.Sc. Mohamed Bourouah, Hahn-Schickard Institut Department: Microtechnology, 78052 Villingen-Schwenningen
German Industrial Partner	Georg Brückner, Sondermaschinenbau Brückner GmbH, 96257 Marktgraitz (until Nov 23)
Indian Research Partner	Dr MURTAZA HASAN, Indian Agricultural Research Institute, Department/Division: Centre for Protected Cultivation Technology ICAR-IARI, 110012, Delhi
Indian Industrial Partner	Shivendra Singh, Barton & Breeze 122101 Gurgaon Haryana
4. Date of Start	01.04.2021
5. Date of Completion	31.03.2024

6a. Objectives/Deliverables as per the approved Project Proposal

In hydroponic systems, the nutrient solution is usually monitored via the EC and pH value as well as the temperature. For a greater nutrient use efficiency, higher plant productivity and better control of desired crop characteristics such as secondary metabolite profiles, taste and appearance an additional continuous monitoring of the ion ratio of nutrient solutions seems a promising solution. Significant advances have been made in recent years in overcoming the technical obstacles on the way to an ion specific fertigation system (see chapter 5 publications by others). Most of these works addressed the control of the ion interference effect, which makes obtaining accurate measurements of the concentration of single ions in complex solutions difficult. Although successful strategies for reliable and accurate measurements of NO₃⁻, K⁺ and Ca²⁺ have been developed, fully functional automated fertigation systems measuring and controlling the concentration of the five major macronutrients also including PO₄⁻ and Mg²⁺ are still lacking, as well as information on how automated ion specific fertigation management performs compared to traditional, EC and pH, based fertigation management.

Therefore, the main objective of the SensVert project is the development of an automated IoT based, ion specific sensor system, for the integration into hydroponic systems, allowing continuous monitoring of NPK, Ca and Mg.

6b. Objectives/Deliverables of the Project to be accomplished by the Partner as per work package distribution

WP 1	Specifications of the ion-selective sensor system inside a vertical farming system
WP 1a (HSWT, IARI)	<ul style="list-style-type: none"> • Definition of the required specifications of the growth systems and specifically the desired functionality of the sensors to be employed.
WP 1b (HSWT, IARI)	<ul style="list-style-type: none"> • Drafting of a catalogue of customer requirements for the ion-specific dosing system to be developed.
WP 1c (All)	<ul style="list-style-type: none"> • Drafting of a specification book with all partners.
WP 2	Construction of small test units
WP 2a (All)	<ul style="list-style-type: none"> • Putting the general specifications of the ion-selective sensor system inside a vertical farming system, the fertigation system and the cultivation system as a whole in concrete terms to design a test unit. • Defining the limits for the composition of the nutrient solution.
WP 2b (HSWT, Brückner GmbH)	<ul style="list-style-type: none"> • Design and construction of two preliminary test units, to be fitted with ISEs later on. EC and pH as control measurements at this stage. • These growth systems should be ready to be equipped with different LEDs and able to record water uptake and EC concentrations for different treatments • Procurement of a fertigation controller, ready for integration into the ion-selective sensor system.
WP 4	Verification of the sensors and functionality in a precise horticultural production system
WP 4a (All)	<ul style="list-style-type: none"> • Functionality test of the test units along with manual adjustment of the nutrient solution • Analytical and manual reference measurement of the nutrient solution and the plants • Definition of sufficient ranges of ion concentrations based on these reference measurements. Documentation of EC and pH. • The plant and nutrient solution parameters observed in these first trails should serve as a reference for later trails. • Selection of test crop • Integration of the ion selective sensors and validation of the interface for display and calibration. • Fine tuning of the Sensing system • Observation of uptake ratios
WP 4b (HSWT, IARI, B&B)	<ul style="list-style-type: none"> • Comparing the ISE measurements to the analytical reference measurements • Evaluation the sensor performance with known solutions: Accuracy, measurement range, resolution, repeatability, saturation, Dead band • Testing of the Sensors in complex solutions
WP 4c (HSWT, HS, Brückner GmbH)	<ul style="list-style-type: none"> • Recording of the ion selective measurement in an online data bank • Automated prompts coupled to pout of range measurements. • Establishing feedback loops for the automated adjustment of out-of-range ions
WP 4d (HSWT, IARI)	<ul style="list-style-type: none"> • Comparing ion uptake ratios in the different cultivations systems at ICAR and HSWT • Improving limit ranges for ion concentrations • Automatic adjustment of ion concentrations by fertigation systems

WP 4e (All)	<ul style="list-style-type: none"> • Evaluation of results thus far, and adjustment of requirements
WP 5	Development of optics system for photometry measurements (HS)
WP 5 (HS)	<ul style="list-style-type: none"> • The development of optical sensors was not pursued due to technical difficulties
WP 6	Interface of IoT System
WP 6 (HS, SMB, B&B)	<ul style="list-style-type: none"> • Development of Hardware and software modules for an automated nutrition management system
WP 7	Requirements for automated nutrient solution strategies (HSWT, IARI)
WP 7a (HSWT, IARI)	<ul style="list-style-type: none"> • Definition of benchmark parameters (Yield per m², up-taken nutrients per day) for the comparison of the cultivation systems at HSWT and ICAR.
WP 7-b (HSWT, IARI)	<ul style="list-style-type: none"> • Development cultivation parameters for testing of fertigation strategies for both cultivation systems such as nutrient use efficiency, influence of climatic factors, effect of different lighting • If more sensors become available, expansion of trails to more plant species
WP 7c (HSWT, IARI)	<ul style="list-style-type: none"> • Development of fertigation strategies
WP 7d (HSWT)	<ul style="list-style-type: none"> • Testing and adaption of fertigation strategies
WP 8	User interface
WP 8 (HS, B&B)	<ul style="list-style-type: none"> • User interface
WP 9	Optimization and Adaptation
WP 9 (HS, SMB)	<ul style="list-style-type: none"> • Optimization and Adaptation of the sensor system to the requirements
WP 10	Coordination
WP 10: (HSWT, IARI)	<ul style="list-style-type: none"> • Coordination
WP 11	Communication and dissemination
WP 11: (HSWT, IARI)	<ul style="list-style-type: none"> • Communication and dissemination

7a. Salient Achievements -Summary of Progress

The main aim of the project was to develop a sensor system for a continuous monitoring of macronutrients in hydroponic nutrient solutions. This sensor system should enable the automatic adjustment of the concentration of individual ions and thus optimize ion-selective fertigation strategies for hydroponic cultivation systems. The demand-oriented, sensor-based dosing of individual nutrients is supposed to improve resource efficiency and productivity compared to conventional EC-based fertilization.

The requirements framework for the use of ion-specific fertigation in hydroponic cultivation systems were defined. A sensor platform for measuring NO₃⁻, K⁺ and Ca²⁺ was developed at the Hahn Schickard Institute, validated in collaboration with the HSWT and optimized for horticultural use. The concentration of the macronutrients NO₃⁻, K⁺ and Ca²⁺ could be determined with the developed sensor system with sufficient accuracy (± 5 %) for the measurement-based adjustment of the nutrient solution.

The handling, the calibration strategy, the measurement processes and the preparation of the measured values were constantly optimized based on a developed procedure (fig. 1).

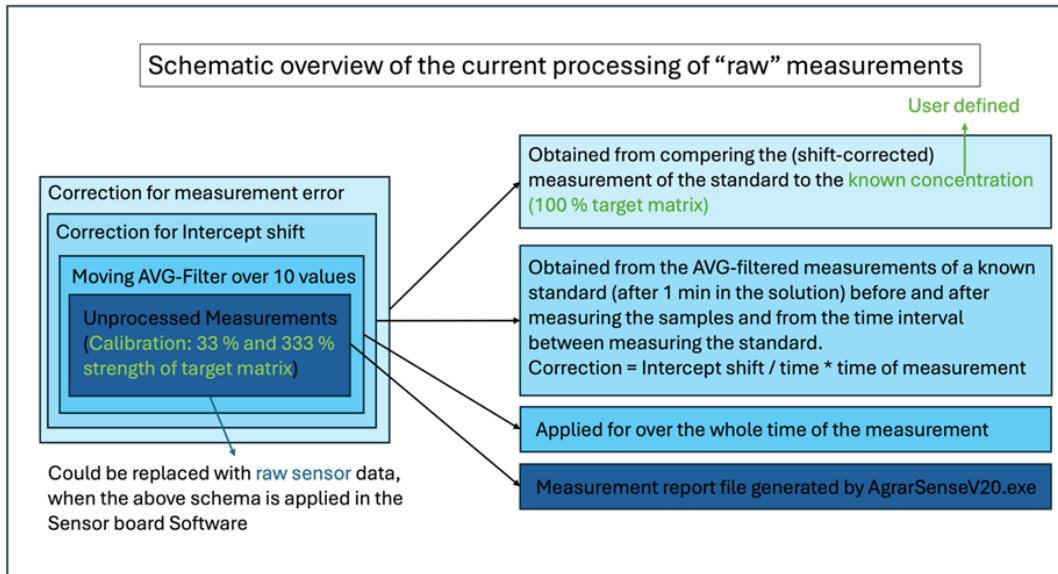


Figure 1: Overview of the calibration and measurement processing scheme developed during the project.

Various approaches were used to measure PO_4 and Mg. A cobalt electrode was developed at the Hahn Schickard Institute for the determination of PO_4 . Due to the technical complexity of the measurement, which requires, among other things, buffering of the pH value and regularly polishing the electrode for new active electrode surface, this was not initially integrated into the prototype sensor unit.

The measurement properties of the ion-selective electrodes (ISEs) in the relevant application scenarios were systematically tested at the HSWT by measuring analytical standards and hydroponic nutrient solutions. The change in the measurement properties of the ISEs was investigated as a function of their age and under different handling conditions. Dry storage and conditioning in a low-concentration solution of the ion to be measured provided the best measurement results over the useful life of the ISEs, which was up to nine months depending on the ion to be measured. Specific calibration strategies for measurements in hydroponic culture systems and solutions for post-processing of the measured values were developed to optimize the measurement accuracy for the specific application scenario. A two-point calibration with ion concentration ratios that correspond as closely as possible to the solution to be determined provided satisfactory measurement results.

The scheme for post-processing the measured values is based on measuring a solution with a known composition before and after measuring the culture nutrient solution. This calibration method in combination with the post-processing scheme enabled the determination of ion concentrations with the accuracy required for the measurement-based adjustment of the nutrient solution (fig. 2). A dosing scheme was developed for post-fertilization of the individual nutrients with fertilizer salts, which enables the independent dosing of individual ions as far as the combination of fertilizer salts used allows. The process schemes developed for calibration, measured value processing and dosing were validated in a hydroponic culture experiment. The concentrations of NO_3^- , K^+ and Ca^{2+} were regularly measured and successfully adjusted to defined target values. The macronutrients could be dosed according to the consumption of the plants, while Mg, SO_4 and PO_4 were dosed according to defined ratios to the other ions.

The final implementation of the measurement and dosing by an automated fertigation system could not be completed within the project period due to technical problems and the withdrawal of a project partner from the project consortium. However, the necessary automatic dosing system for the various solutions was developed at the Hahn Schickard Institute together with a comprehensive software solution capable of reading various parameters crucial for hydroponic systems, including ISE (nitrate, potassium, calcium), EC, pH, temperature and an intuitive user interface (fig 3). The developed hardware was dispatched to IARI & B&B, where it facilitated precise measurements within the hydroponic unit using the Hahn-Schickard user interface. Furthermore, Hahn-Schickard developed a hybrid communication system combining LoRa and NB-IoT technologies. This hybrid approach ensures that the system meets current field requirements, providing robust and reliable data transmission across diverse environments. These combined capabilities extend communication coverage to both rural and urban areas. Collaborating with subcontractor AgrarSystem, an NB-IoT communication interface was developed.



Figure 2: Decision tree to determine the single salt stock solutions and dosing volumes to achieve the amounts of individual ions required for the adaption of the nutrient solution.

The use of measurement-based single-ion adjustment in hydroponic crop production holds potential for improving fertilizer use efficiency and could facilitate the use of sustainable fertilizers with unknown and fluctuating compositions.

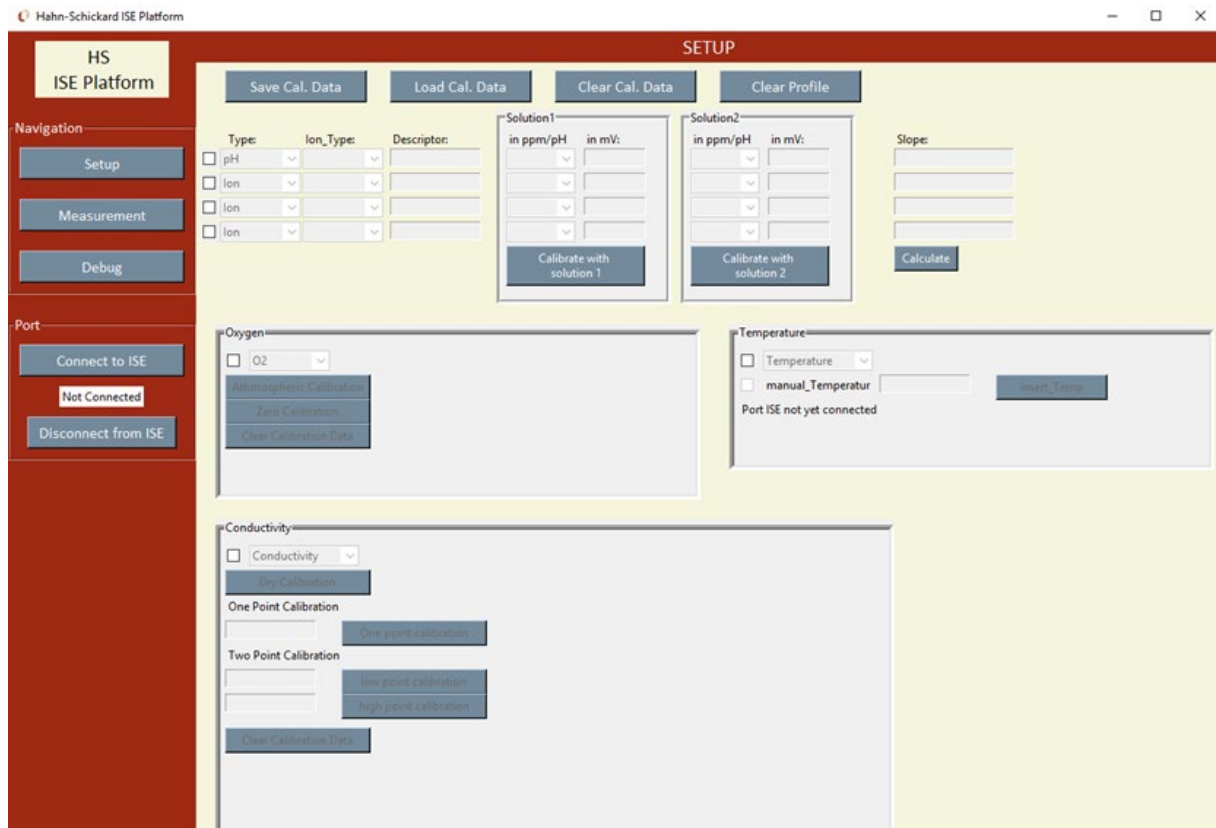


Figure 3: Developed Graphical user interface

7b. Objectives/Deliverables met (please explain)

No.	Title	Responsible Partner	Details
1	Specification defined	All	The specifications for the implementation of an ion-specific fertigation system in hydroponic plant production were discussed and defined.
2	Sampling system designed	HS, B&B	A microfluidic sampling system designed to handle the loading of calibration, storage, and sample solutions to the ISE-flow cell was developed by Hahn Schickard. The specifications for the integration with a control nodes; i.e. physical channel addresses and voltage levels were documented
3	Potentiometric system analysis designed	HS	Hahn Schickard designed and delivered a Sensor platform, to process ISE raw signals for calibration, measurement and reporting. This system was used to thoroughly test ISE performance at HSWT
4	Testing hydroponic units installed, ready for plant trials	HSWT, Brückner, IARI	Hydroponic test units ready for the integration of the prototypes of the ion-selective fertigation unit were installed at HSWT and IARI. Cultivation trails were performed with these test units to determine system properties relevant for fertigation (Nutrient solution turnover rate, homogenization of the nutrient solution).
5	Climate controlled greenhouse based vertical farm	HSWT, Brückner, IARI	A hydroponic test unit was installed within a climate-controlled greenhouse environment at IARI. The test unit was installed in an artificial light environment at HSWT.
6	Optical system analysis designed	HS	The development of optical sensors was not pursued due to technical difficulties. The System for phosphate detection is based on Molybdat-Vanadat-Methode, the system can be used only in manually due to the complex reagent handling. Due to the combined salt ratio, the phosphate amount is estimated using the decision tree in fig 2.
7	Fertigation scheduling strategy for different horticultural crops grown in vertical farm	IARI	IoT and sensor based fertigation-scheduling strategy for horticultural crops including green leafy vegetables like lettuce and pak choy was developed at IARI. ISE-based ion-selective fertigation strategies for lettuce were developed at HSWT using the ISE-sensor platform designed by Hahn Schickard institute. In previous trails ion- specific nutrient uptake was characterized for pac choy, as part of testing spectrophotometric nutrient determination as a reference for the ISE-measurements.
8	Standardized sensor values for different stages of selected horticultural crops	IARI, HSWT	For the crops used in the cultivation, trails with ion-specific fertigation target values for the controlled ions were fixed throughout the cultivation period at both locations.
9	Results dissemination and potentials evaluation	All	The results achieved within the project tenure have been implemented in a lecture on the potential of ion-specific fertigation at HSWT. Hahn Schickard Institute is pursuing the completion of the automated fertigation unit with an IoT interface beyond the official end of the project, as the prototype and the corresponding IoT-software, are close to being ready for a test run in a plant cultivation trail. In April 2024, Hahn-Schickard highlighted the MFSS at Embedded World 2024 in Nürnberg, Germany (refer to Figure below). Currently, discussions are underway with various industry companies regarding further development and commercialization opportunities.

8. Details of Research Staff hired/worked

S. No	Name	Position	Date of joining & leaving	Educational qualifications	Salary/ Fellowship
1.	Markus Abel	Research fellow	15.07.2021 – 31.03.2024	Master: Agricultural management	
2.	Sabine Wittmann	Research fellow	01.01.2024 - 31.03.2024	Master: Horticulture	
3.	Dr. Love Kumar	Research associate	20.07.2021- 27.11.2022	Ph.D.	Rs. 47000/- (per month) plus 24% HRA
4.	Dr. Paradkar Vinayak Digambar	Senior research fellow	28.07.2021 – 06-03-2024	Ph.D.	Rs. 35000/- (per month) plus 24% HRA
5.	Mr. Navneet Sharma	Research associate	28.02.2023 – 24-04-2023	Ph.D.	Rs. 47000/- (per month) plus 24% HRA
6.	Ms. Pragya Balley	Research associate	24-04-2023 – 08-12-2023	M. Tech.	Rs. 47000/- (per month) plus 24% HRA
5.	Mr. Prashant Kumar	Skilled worker	20.07.2021- 29.02.2024	ITI	Rs. 14000/- (per month consolidated)
7.	Mohamed Bourouah	Research fellow	01.06.2021 31.03.2024	M.Sc	
8.	Mohannad Aljebbawi	Research fellow	01.06.2021 31.03.2024	B.Sc	

9. Details of Exchange Visits/Conference participation made

S. No	Name	Give details
1.	Visit of India project partners to the German project partners	Dr. Hasan principal scientist at the ICAR and Mr. Shivendra CEO of B&B attended the IGSTC partners meet in Frankfurt on the 15.06. and 16.06.2022 to present the SensVert project. Subsequently Dr. Hasan and Mr. Shivendra visited the faculty for Horticulture of the HSWT and the facilities of Hahn Schickard Institute and returned to Delhi on the 27.06.2022.
2.	International horticultural congress (IHC) 2022	A Delegation of the Applied Science Centre (including Markus Abel and Heike Mempel) of the Faculty for Horticulture at the HSWT attended the IHC 2022 in Angers to present the congress proceedings listed in section 10 (A)
3.	Visit of German Project Partners to the Indian project partners	From the 02.03.2023 until the 10.03.2023 Mr. Abel project investigator of the HSWT and Mr. Bourouah, principal scientist at the Hahn Schickard Institute visited the facilities of the ICAR and B&B in Delhi.

10. Science and Technology Benefits accrued / List of Publications from this Project, if any (including title, author(s), journals & year(s) (Please specify if any joint publications)

(A) Papers published only in cited Journals (SCI) as part of the project (Joint publication, if any)

S. No	Authors	Title	Journal details	Year
1.	Kishor P. Gavhane, Murtaza Hasan, Dharendra Kumar Singh, Soora Naresh Kumar, Rabi Narayan Sahoo & Wasi Alam	Determination of optimal daily light integral (DLI) for indoor cultivation of iceberg lettuce in an indigenous vertical hydroponic system	Scientific Reports	2023

(B) Papers published in Conference Proceedings, Popular Journals etc.

S. No	Authors	Title	Conference details	Year
	M. Abel, S. Wittmann, I. Jüttner, H. Mempel,	Identification of variations in nutrient uptake ratios of Pak Choi (Brassica rapa) as an indicator for the potential of ion-specific nutrient management.	<i>Acta Horticulturae 2022 XXXI International horticultural congress (IHC 2022): International Symposium on Advances in Vertical Farming</i>	2023
	H. Mempel, M. Hasan, M. Bourouah, S. Kumar, I. Mani, L. Kumar, V. Paradkar, M. Abel, S. Wittmann, I. Jüttner	Design and Development of Automatic Nutrient Sensors for Efficient Water and Nutrient Management in Vertical Farming	<i>Acta Horticulturae 2022 XXXI International horticultural congress (IHC 2022): International Symposium on Advances in Vertical Farming</i>	2023

(C) Intellectual Property generated:

S. No	Authors	Title	Country/other details	Year
	none			

(D) PhD/Master thesis supervised

S. No	Name	PhD/Masters	Title of the Thesis	Year
1.	Gavhane Kishor Pandurang	PhD	Development of sensor-based automated fertigation system for vertical farming	2023

2.	Poojan Jariwala	M.Sc.	Design and Automation of Control Panel for Hydroponic Farming	2023
3	Markus Abel	M.Sc	Konzeption und Integration einer Bewässerungssteuerung für eine hydroponische Growbox	2023

11. Equipment/consumables procured under the project (costing more than Rs 1 lac)

S No	Name of equipment /consumables	Model & make /quantity	Date of procurement	Cost (Rs in lac)
1	Fertigation and Climate Controller	Make: Jain Irrigation Pvt. Ltd. Jalgaon	19.03.2022	9.78
2	Aeroponic and Hydroponic Management Kit	Make: Shailron Technology Pvt. Ltd.	23.03.2022	7.90

12. Representative photographs of the project (please attach separately in jpeg format)



Fig 4: IoT and Sensor Operated Greenhouse Vertical Farm (1000 sq meter)

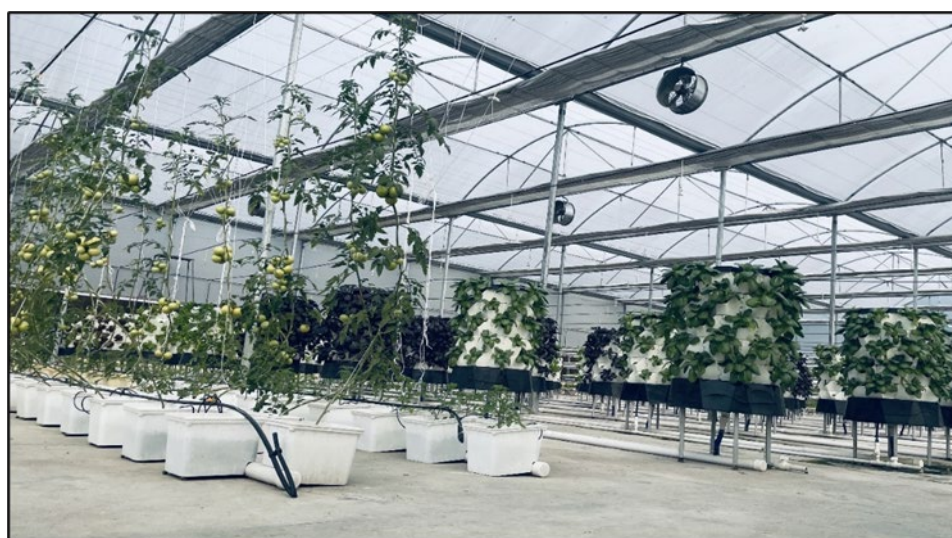


Fig 5 : Dutch Bucket and Grow Tower Facilities inside Greenhouse Vertical Farm



Fig 6: Hahn-Schickard showcase of the MFSS at Embedded World 2024 in Nürnberg, Germany

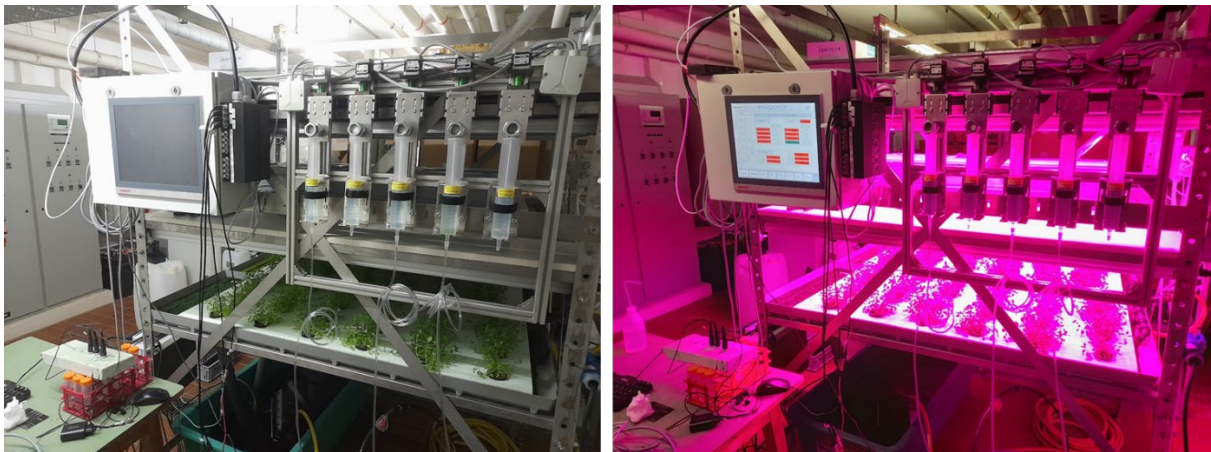


Fig.7: Experimental set up in the hydroponic test unit for vertical farming at HSWT



Fig. 8: A Frame and Flat Frame Vertical Hydroponic Facilities in Greenhouse Vertical Farm



Fig. 9: Plant Factory developed inside Greenhouse Vertical Farm



Fig 10: IoT and Sensor based Fertigation Controller

13. A one-page write up (with photograph) on project completion, which can be published in Annual Report of IGSTC.

The SensVert project aimed at achieving ion-specific monitoring and adaption of hydroponic nutrient solutions based on ion selective electrodes (fig. 1).

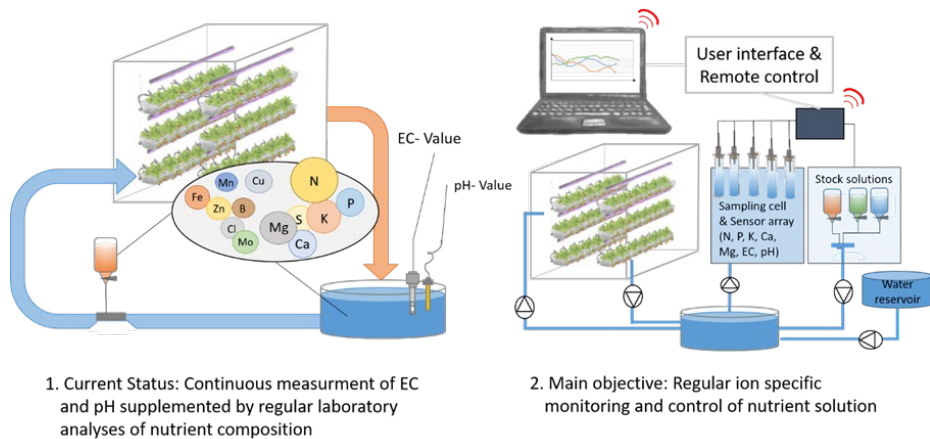


Figure 1: Main objective of the SensVert-Project

The project tenure ended in March 2024 with successful tests for the implementation of ISE-based ion-selective fertigation strategies in hydroponic plant cultivation. A custom-made board for ISE signal acquisition with a match software for signal processing enabled precise determination of NO_3 , K and Ca with commercial polymer-membrane ISEs. The limited lifespan along with the cost of the ISE-sensors poses a major challenge to their commercial use. Efforts were made to closely monitor the performance of the Sensors and to find optimal handling and calibration procedures at HSWT and ICAR. Strick dry storage and minimized exposure of the ISEs to ion-solutions yielded the most stable sensor performance. This handling procedure along with two-point calibration in dilutions of the stock solution containing all nutrient ions and a measurement-error correction based on measurements of a known standard enabled single ion adaption to target values of the nutrient solution with a high degree of precision (less than 5 % error). A dosing algorithm was developed to address the problem of ion-coupling in single salt stock solutions to achieve precise addition of required ion quantities with available fertilizer salts. Concentrations of the controlled macro ions remained close to target values in the ion specific control treatment throughout the 30-day cultivation trail with lettuce, while in the EC-based control treatment with fixed ion replenishment ratios potassium concentrations dropped to below 10 ppm towards the end of the cultivation and Calcium concentrations were continuously increasing. For the automated implementation of the dosing algorithm, the calibration scheme and the measurement correction based on a known standard a micro fluidic sampling system was developed. At the end of the project, the software for implementing the control logic and the user interface of the alternative fertigation controller Fertigation was in the test phase. The results of the project indicate that ISE-based ion-specific nutrient management in commercial hydroponic cultivation is feasible and could contribute to an increased productivity in horticultural production by enabling optimized fertigation strategies with improved nutrient use efficiency, while at the same time promising to reduce the environmental footprint of horticultural production through decreased fertilizer demand and nutrient discharge.

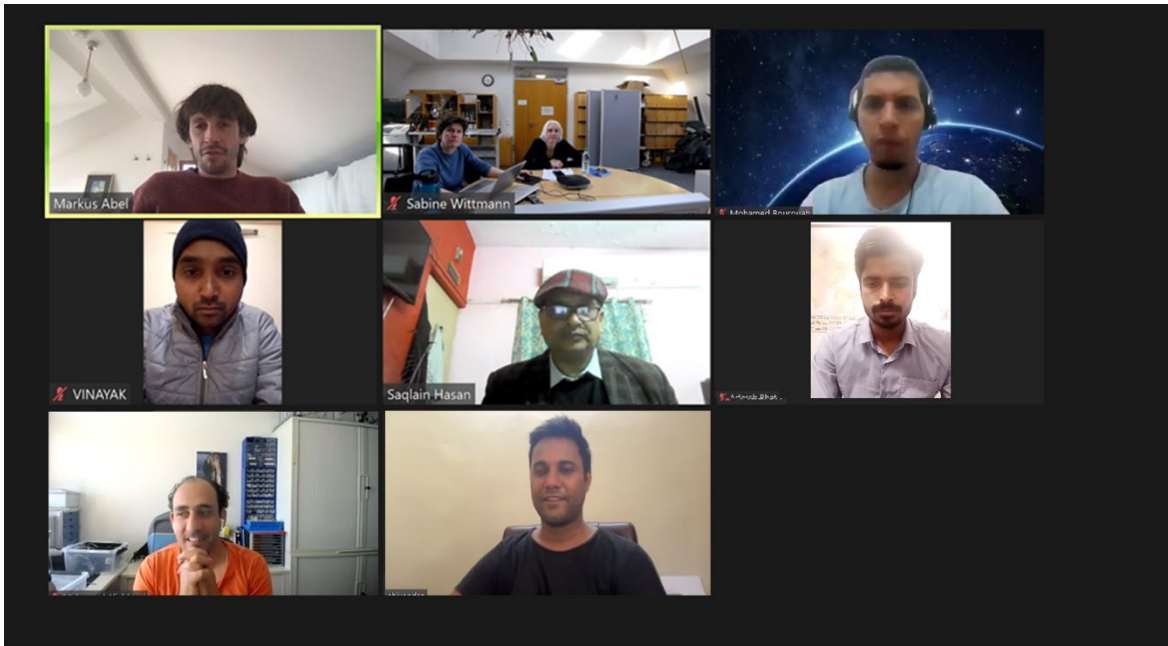


Figure 2: project partners meeting via zoom

Signature of PI Date:
(with seal/stamp)